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GEOTHERMAL PUMPING SYSTEMS AND TWO-PHASE FLOW STUDIES

by

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ABSTRACT

Improvements in electric submersible pumping systems have resulted in a demonstrated downhole running life of one year for low horsepower units operating in 180°C brine. The implementation of a prototype pressurized lubrication system to prevent brine intrusion and loss of lubricating oil from the motor and protector sections has been successfully tested. Second generation pressurized lubrication systems have been designed and fabricated and will be utilized in downhole production pumping tests during FY 84. Pumping system lifetime is currently limited by available power cable designs that are degraded by high-temperature brine. A prototype metal-sheathed power cable has been designed and fabricated and is currently undergoing destructive and nondestructive laboratory testing. This cable design has the potential for eliminating brine intrusion into the power delivery system through the use of a hermetically sealed cable from the surface to the downhole motor.

The two-phase flow program is directed at understanding the hydrodynamics of two-phase flows. The two-phase flow regime is characterized by a series of flow patterns that are designated as bubble, slug, churn, and annular flow. Churn flow has received very little scientific attention. This lack of attention cannot be justified because calculations predict that the churn flow pattern will exist over a substantial portion of the two-phase flow zone in producing geothermal wells. The University of Houston is experimentally investigating the dynamics of churn flow and is measuring the holdup over the full range of flow space for which churn flow exists. These experiments are being conducted in an air/water vertical two-phase flow loop. Brown University has constructed and is operating a unique two-phase flow research facility specifically designed to address flow problems of relevance to the geothermal industry. An important feature of the facility is that it is dedicated to two-phase flow of a single substance (including evaporation and condensation) as opposed to the case of a two-component two-phase flow. This facility can be operated with horizontal or vertical test sections of constant diameter or with step changes in diameter to simulate a geothermal well profile.

GEOTHERMAL PUMPING SYSTEMS

I. BACKGROUND

The goal of the geothermal pump program is to demonstrate the reliability and performance of high-capacity electric submersible pumping systems that could be used to supply brine to the 50-MW Geothermal Demonstration Plant at Heber, California. Accomplishment of this goal will be achieved by stimulating the development and extensive testing of improved electric submersible pumping systems that have been hardened to survive the conditions imposed by production pumping of hot brines. Downhole pumping of geothermal wells offers the potential for several significant benefits including enhanced flow rates that reduce the number of wells required, elimination or reduction of well-bore chemical precipitation and scaling through downhole pressurization, higher wellhead brine temperatures for increased energy conversion efficiency, and single-phase fluid distribution lines on the surface as opposed to separate steam and brine piping to the power plant.

II. STRATEGY

The initial thrust of the geothermal pump program was to provide a Geothermal Pump Test Facility (GPTF) that could be used by electric submersible pump manufacturers to test pumping systems under realistic geothermal production conditions. Although this facility has been used extensively by REDA, CENTRILIFT, and KOBE pump companies, only REDA has actively pursued the development of a specialized geothermal product line.

The heart of the successful REDA geothermal pumping system is the vastly improved series 540 motor. REDA has concentrated their geothermal development efforts on the series 540 motors, partially because of their reliability and popularity in oil field service, and also because of the extensive testing on the series 540 80-horsepower units in the GPTF and at East Mesa. The recently completed 11-month endurance test of a REDA 80-horsepower geothermal pumping system at East Mesa has demonstrated that the present engineering design and materials can survive with very little degradation in 180°C brine if brine intrusion into the motor and power cable can be eliminated or minimized. To extrapolate the results from this test to a typical production pumping scenario in the Imperial Valley, the following concepts must be demonstrated through extensive testing:

- That high-horsepower tandem motor pumping systems can be operated with the reliability already demonstrated by the 80-horsepower units.
- That a continuous metal-sheathed cable can be developed that will eliminate brine intrusion into the power cable and pothead assembly, thus eliminating the steady degradation observed in present day cables.
- That a pressurized downhole lubrication system can be tested that will eliminate brine intrusion into the motor sections, and will operate at any pump setting depth.

It is the objective of the geothermal pump program to demonstrate these concepts through continued testing in the GPTF, through high-horsepower unit testing in production wells in the Imperial Valley, and through subcomponent testing in both the GPTF and in laboratory facilities.

III. ENDURANCE TEST AT EAST MESA

A series 540 80-horsepower REDA geothermal pumping system completed an 11-month production pumping test in well #6-2 at East Mesa during the last quarter of 1982. The pump was used to supply brine to the 500-kW binary power plant. The brine temperature was 180°C, and the pump nominally produced 220 GPM at a wellhead pressure of 300 psi. This unit was equipped with a Barber-Nichols designed and installed pressurized lubrication system. The pumping system was pulled from the well after 11 months of operation because of steadily declining pump performance as indicated by a declining flow rate and wellhead pressure. At the time the unit was pulled, the motor performance was still satisfactory and testing would have been continued were it not for the poor pump performance.

Although every effort is made to minimize shutdowns on pumping systems installed in geothermal production wells, the combination of power plant shutdowns, planned electrical system maintenance, and power interruptions during severe storms results in the pumping systems being turned off and cooled down on the order of eight times a year. The ensuing cool-down and heat-up after the pump is restarted produce substantial contraction and expansion of the motor oil, which must be compensated for by the motor expansion chamber bellows and pressurized lubrication system. These shutdowns provide an opportunity for taking phase-to-ground resistance readings of the motor/cable system. During testing of the 80-horsepower unit at East Mesa, significant changes in the motor/cable phase-to-ground resistance readings were observed. These changes included the long-term deterioration of the motor/cable system resistance along with short-term variations noted during the shutdowns. The long-term deterioration of the system is illustrated in Fig. 1 with a final phase-to-ground resistance of approximately 250,000 ohms when the pump was shut down.

After removal from the well, the phase-to-ground resistance of the motor was measured separately as 2,000 megohms, confirming that the oil pressurization system had kept the motor dry and free from brine intrusion. For comparison purposes, the overhauled replacement motor supplied by REDA was also checked, and its phase-to-ground resistance was measured as approximately 2,000 megohms. The deteriorating phase-to-ground resistance was, therefore, a function of cable degradation rather than an impending motor problem.

The apparently excellent condition of this motor was further verified after a complete teardown inspection was performed at the REDA plant. All thrust and radial bearings were found to be in like new condition, there was no evidence of brine intrusion, the motor oil was clean, the expansion bellows

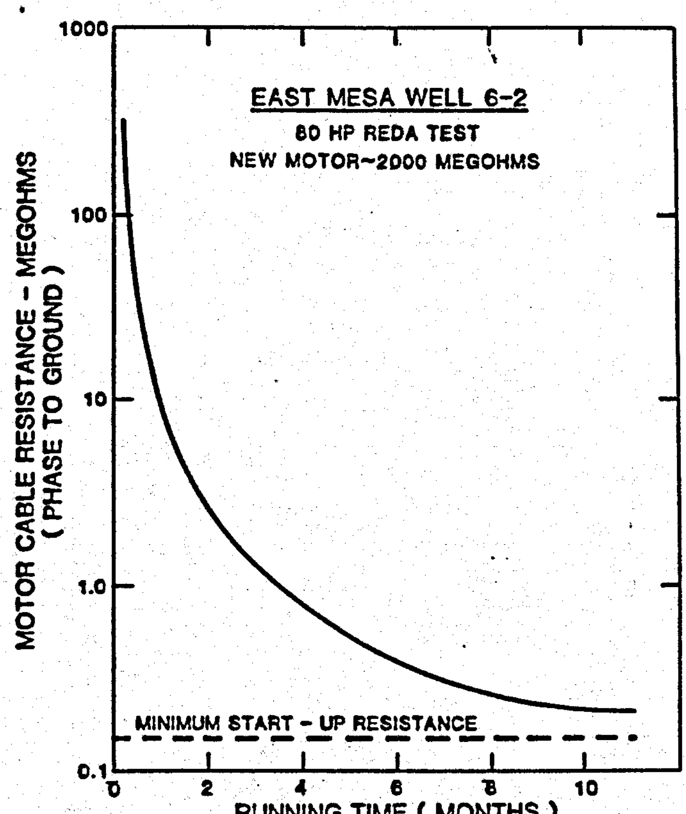

Fig. 1. Phase-to-ground resistance vs running time for 80-horsepower endurance test at East Mesa.

looked like new, the seals showed very little sign of visible wear, and it was conjectured that this motor could have run another year under the same conditions. The protector was also in excellent condition; it was filled with clean oil and showed no signs of brine intrusion. The protector thrust bearing, which supports the pump downthrust load, was also in very good condition with only a few light wear marks. This bearing is illustrated in Fig. 2 where the excellent condition of the tilting pad surfaces can be seen.

Almost all the pump impeller and diffuser stages showed excessive mechanical wear explaining the poor pump performance. Evidence obtained during the pump disassembly showed that the pump impellers' labyrinth seals were worn, this wear probably being initiated by abrasive material in the brine. With the labyrinth seals leaking, pressure balancing of the pump stages was lost creating additional downthrust on each pump impeller stage. This additional downthrust destroyed the leading edge thrust bearings and ultimately allowed mechanical contact between the rotating impellers and the stationary diffusers. Eventually the impeller front shrouds were completely worn away and numerous impeller vanes were either broken free or mechanically worn down. The impeller rear hubs, which function as radial bearings, were also worn away on most of the impellers. This destructive wear is illustrated in Figs. 3 and 4. It

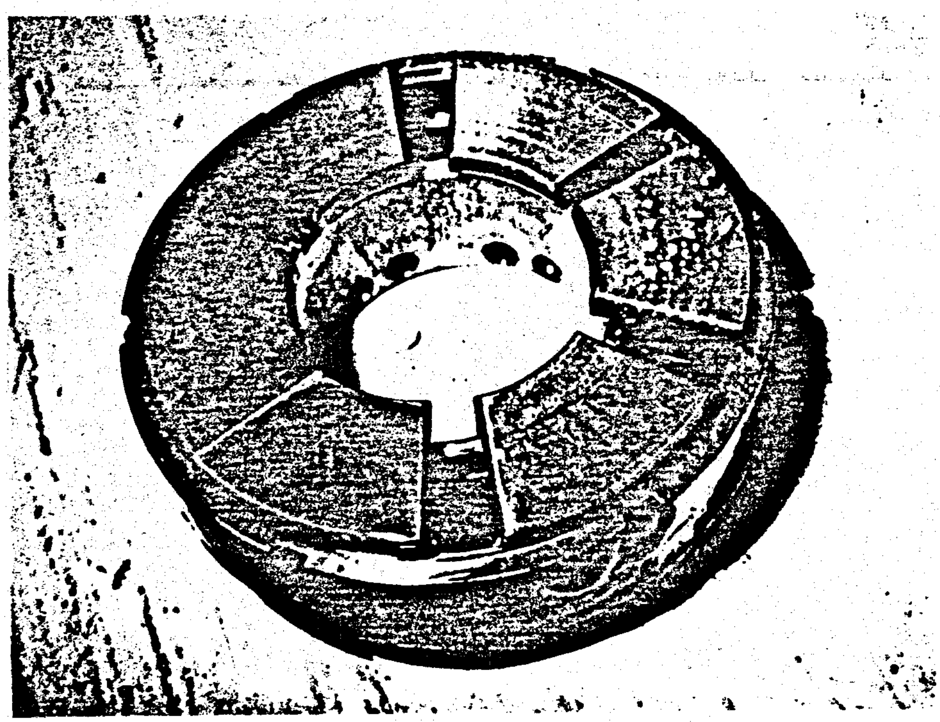

Fig. 2. Tilting pad surfaces of protector thrust bearing after 11-month test.

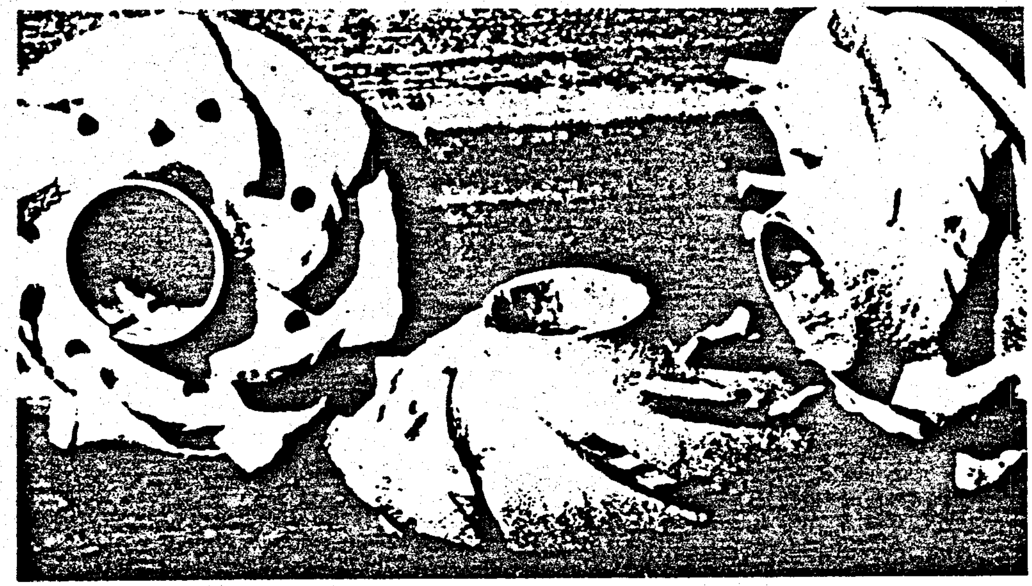

Fig. 3. Severly worn impeller vanes and missing front shrouds.

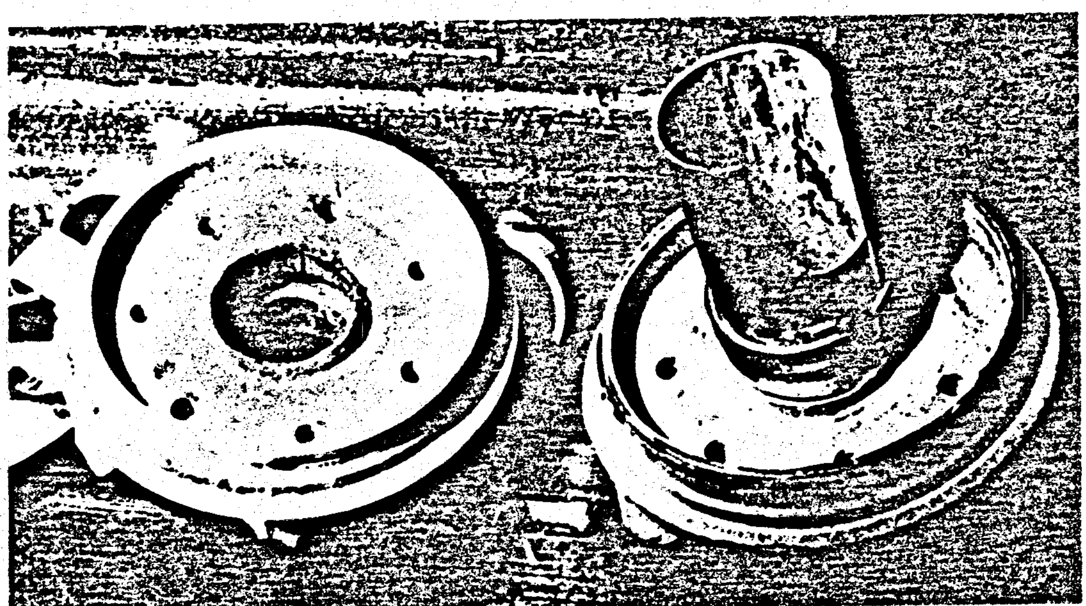

Fig. 4. Excessive wear on impeller hubs and shrouds.

should be noted that this is a standard oil field pump without any geothermal modifications.

IV. PRESSURIZED LUBRICATION SYSTEMS

A. N_2/Oil Accumulator with Bubble Tube

The Barber-Nichols developed pressurized lubrication system uses nitrogen gas pressure in an oil accumulator tank to pressurize the motor oil to the desired level. The accumulator tank is connected to the motor with a small diameter injection pipe and inline filter assembly. A nitrogen bubble tube is placed in the well adjacent to the motor section to measure the brine pressure at this depth. When the brine pressure is determined from the bubble tube, the nitrogen gas pressure in the oil accumulator tank is adjusted to provide a small oil overpressure in the motor housing. The pressure relief valve in the protector section will open to bleed off excessive oil pressure if the motor is accidentally overpressurized from the surface supply line. The Barber-Nichols N_2/oil accumulator system has two distinct disadvantages for a commercialized downhole lubrication system.

1) In addition to the oil flow line, it requires a separate bubble tube line set to the pump depth; and bubble tubes frequently plug necessitating pulling and cleaning.
2) The system cannot be used on deep-set pumps where the hydrostatic head of the oil column exceeds the desired oil pressure in the motor housing.

As a proof-of-concept test, however, the Barber-Nichols system performed exceptionally well during the endurance test. The almost brand new condition of the motor and protector after an 11-month running period serves as adequate testimony to the effectiveness of a pressurized lubrication system. This system is illustrated in Fig. 5 as it was installed at East Mesa. The nitrogen bottles are used for the bubble tube and to control the pressure of the motor oil in the accumulator tank pictured in the center of the installation.

B. Oil Metering Pump with Relief Valve Bleed

REDA has provided a POSI-LIFE pressurized motor lubrication system for testing on the 300-horsepower pumping system in a MAGMA production well at East Mesa. This system eliminates the bubble tube and can be used at any pump setting depth. Using a surface-mounted oil metering pump, it provides an essentially constant flow of oil to the downhole motor. The oil pressure in the motor is controlled by the protector relief valve, which allows a constant oil bleed from the motor to the external brine. This system has the advantage

Fig. 5. Barber-Nichols pressurized lubrication system installed at East Mesa well 6-2.

of providing a small, continuous fresh supply of oil to the motor, which should improve the quality of the lubricant during long production pumping intervals. It also assures that the motor is completely immersed in oil because the oil bleed valve is at the top of the protector. Only very limited field test data has been obtained on this system to date. An oil bleed unit of this type has the following potential disadvantages:

1) Because the motor oil pressure is controlled by discharge through the protector relief valve, a steady stream of oil is introduced into the produced brine.
2) If the relief valve fails or its discharge port plugs with scale, the motor can be overpressured with oil, which could result in a failed seal and brine intrusion. The discharge port of the relief valve did plug during the 80-horsepower test at East Mesa.

C. Downhole Pressure Regulator

Based on the above considerations, potentially the most universal and reliable pressurized lubrication system is one that incorporates a downhole pressure regulator that senses the differential pressure between the motor oil and the external brine. If the differential pressure between the motor oil and the brine drops below the regulator's preset value, the regulator will open a valve allowing oil under pressure to flow into the motor. When the motor oil pressure increases to the desired level above the brine pressure, the regulator closes the oil valve and oil flow stops. This system operates independent of pump setting depth because the pressure regulator always references the motor oil pressure to the external brine pressure. With this system, the protector relief valve functions only as an emergency backup in the event the motor is accidentally overpressurized through a pressure regulator malfunction. This redundancy is an important feature when assessing the overall reliability of a downhole pumping system. Nominally the motor oil would be pressurized to 3-5 psi above the external brine pressure, a value sufficiently high to prevent brine intrusion while still minimizing the seal forces.

Barber-Nichols has been performing component tests on commercially available pressure regulators at 195°C in water. Material failures in some regulator components were initially experienced under these conditions. Barber-Nichols has fabricated new components from acceptable materials, and the pressure regulators are now surviving at 195°C. These tests will be followed with additional laboratory tests in a simulated East Mesa brine. When reliable pressure regulator operation has been demonstrated, Barber-Nichols will fabricate a downhole pressurized lubrication system based on the pressure regulator concept, and this system will be installed on an 80-horsepower REDA pumping system when it is placed in the GPTF for testing. A schematic drawing

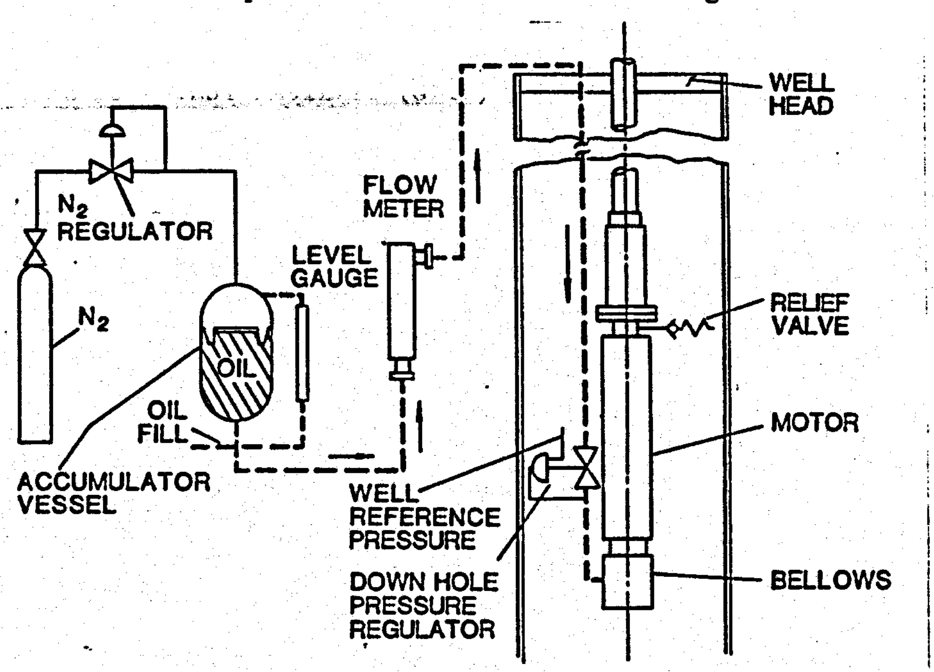

Fig. 6. Downhole pressure regulator controlled motor lubrication system.

of the pressure-regulator-controlled lubrication system is illustrated in Fig. 6.

V. METAL-SHEATHED POWER CABLES

Since the initiation of testing electric submersible pumping systems in geothermal wells, degradation and failure of some portion of the power cable system has been the most reoccurring problem to date. The most common forms of failure have been:

1) Mechanical abuse of the cable during pump installation, resulting in brine intrusion through the damaged area.
2) Installation errors in the packoff where the power cable enters the wellhead, leading to brine intrusion and cable failure.
3) Cable/pothead failures where the cable enters the pothead, leading to brine intrusion and failure.
4) Without any evidence of an abused or damaged area on the cable, brine penetration into the cable, apparently through small leaks in the protective lead sheath.

The declining phase-to-ground resistance readings observed on the 80-horsepower pumping system at East Mesa were obviously an indication of cable deterioration rather than an impending motor problem. The pothead and packoff region were inspected and found to be in excellent condition. No obviously damaged regions on the cable could be located. The suspected cause of cable deterioration must once again be attributed to a pinhole leak in the protective lead sheath, which resulted in brine penetration into the Kapton insulation layer of one of the three-phase power conductors. Detecting the location of the brine intrusion is an almost impossible task unless some visible damage or distortion can be located on the outside surface of the cable. It should be noted that the cable on the 80-horsepower unit did not fail and it was operating the motor satisfactorily when it was pulled. It was, however, deteriorating rapidly.

Just as the use of a pressurized lubrication system is regarded as the solution to brine invasion into the motor section seals, encapsulating the power cable in a continuous metal sheath that is welded or silver soldered to the pothead is envisioned as the final solution to the cable deterioration problem. A materials investigation was initiated to determine suitable candidates for the metal sheath material. Based on coupon samples tested extensively in East Mesa geothermal brines, three metals were identified that have excellent tolerance to a high-temperature brine environment. They are Inconel 625, Hastelloy C, and Allegheny Ludlum 29 chrome-4 moly steel alloy. Many of the popular stainless steels exhibit definite stress corrosion cracking tendencies in hot brine and must be eliminated. In general, the alloying elements that provide the greatest resistance to attack by hot geothermal brines are molybdenum and chrome.

Inconel 625 welded sheaths have been used for small-diameter high-temperature logging and instrumentation cables for geothermal service. Although Inconel 625 is an excellent material with good fabrication qualities, for large-diameter power cables its very high cost becomes a severe disadvantage. A cost comparison, normalized to 304 stainless steel, is presented in Table I.

Allegheny Ludlum 29 chrome-4 moly is being used in the heat exchanger tubes for the Chevron plant at Heber. It is definitely the preferred choice for the metal-sheathed power cable.

Halpen Engineering has proposed a prototype 4-kV cable consisting of a #2 solid copper conductor, three layers of mica insulation, one layer of PTFE teflon insulation, and a 0.020-in AL 29-4 steel sheath. Halpen would supply this cable as a single-conductor cable as they do not presently have the capability of fabricating an outer protective sheath over the three-conductor flat cable assembly. Halpen provided laboratory test data that indicated the proposed cable did not show any evidence of corona activity below an applied voltage of 6000 volts.

Table I

MATERIAL COST COMPARISON

304 STAINLESS STEEL	1
ALLEGHENY LUDLUM 29 CHROME - 4 MOLY	~1
INCONEL 600	4.9
INCONEL 625	9
HASTELLOY C.	8.7

REDA and Los Alamos have purchased 250 ft of single conductor prototype cable from Halpen Engineering. Three 50-ft lengths will be used to form a 50-ft, three-conductor cable for use in the GPTF to run an 80-horsepower pumping system. A protective outer sheath will not be required for use in the GPTF although it would be needed for a production well test. The two remaining 50-ft lengths will be provided to REDA and Barber-Nichols for both destructive and nondestructive laboratory testing. Pending successful laboratory evaluation of the prototype cable samples, negotiations will be conducted with Halpen Engineering for a production cable that can be used in a MAGMA well at East Mesa. The proposed production cable is illustrated in Fig. 7.

Halpen Engineering feels strongly about applying at least two continuous fusion welded AL 29-4 steel sheaths around an electric submersible power cable. If for any reason a metallurgical flaw is present in one of the sheaths, the second sheath will still prevent brine intrusion.

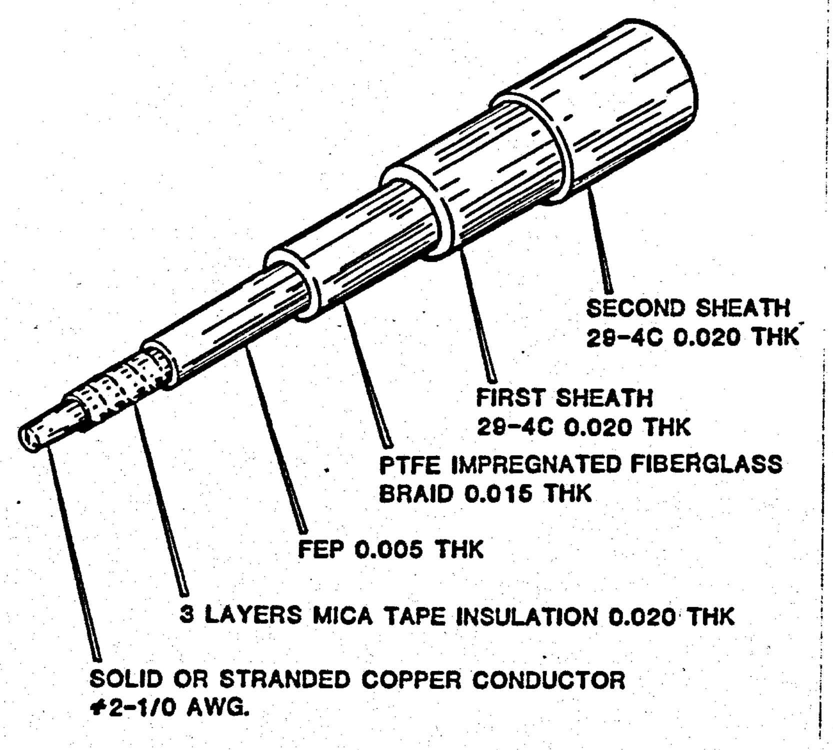

Fig. 7. Proposed Halpen Engineering metal sheathed production power cable.

VI. MAGMA PRODUCTION WELL PUMP TESTS

A. 300-Horsepower Pump Test at East Mesa

IMPERIAL MAGMA is currently operating a 7-MW binary geothermal power plant at East Mesa, California. MAGMA expressed an interest in testing the new REDA geothermal product line of electric submersible pumping systems under production conditions. A 300-horsepower unit is required for the MAGMA wells and two 150-horsepower series 540 geothermal motors operating in tandem were selected. The pumping system was supplied with a prototype version of the REDA POSI-LIFE pressurized motor lubrication system for field evaluation. Because the required setting depth for the pump is 1500 ft, the Barber-Nichols developed lubrication system utilizing a bubble tube could not be used.

The 300-horsepower REDA geothermal pumping system was installed in MAGMA well 44-7 at East Mesa and began production pumping on 6 March 1983. Lack of experience in installing geothermal pumping systems once again manifested itself during this installation and a number of relatively minor but very inconvenient delays were experienced. The major source of problems was related to vacuum filling the tandem motor units with the very viscous synthetic motor oil when the ambient air temperature was low. Despite the fact that the oil was preheated to 105°C before filling, the combination of small diameter fill lines and the large thermal mass of the cold motors made this a slow operation. REDA is currently modifying their oil filling equipment to eliminate this difficulty. A photograph of the REDA geothermal vacuum filling unit is illustrated in Fig. 8. This unit evacuates the air from the motor sections and pumps the heated synthetic oil into the motors under a vacuum.

The only serious problem encountered during the installation was the sudden appearance of an "open" or loss in continuity in one cable leg while the pumping system was being lowered into the well. The unit was pulled from the well, its oil was drained, and the pothead was removed. When the pothead was removed, the connections between the pothead and the motor leads pulled apart with very little effort. The cable and motor were each meggered separately and each measured 2000$^+$ megohms phase-to-ground, indicating that the source of the "open" was apparently a loose motor lead connection. When these leads were made up the next time, they were crimped together to assure tight connections. After refilling with oil, the unit was again installed in the well and all megger readings were normal during the installation.

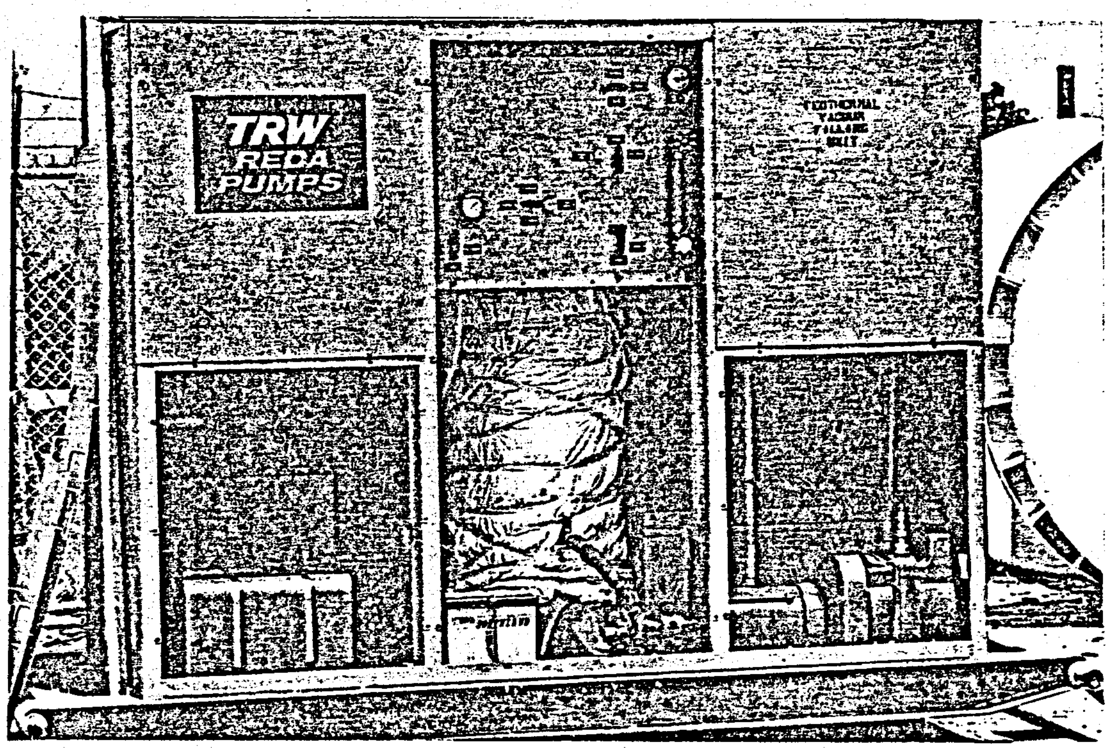

Fig. 8. REDA geothermal vacuum oil filling unit skid.

The pumping system operated normally until a power interruption occurred on 22 March. The pump was delivering over 600 GPM at a wellhead pressure of 275 psi, and MAGMA noted excellent stability of the well field during this production interval. After the pump was restarted, it tripped out on overload, and further attempts to restart the unit were unsuccessful. The pumping system was pulled from the well, and surface inspection revealed that a massive "short" had occurred in the pothead region. The pothead was literally destroyed from the resulting arc.

A teardown inspection was performed on the failed unit at the REDA plant. Most critical elements of the motors, protector, bellows, pump, and cable splice were found to be in excellent condition. Some sand erosion of the pump impellers was evident; however, sand production from a well is normally the highest when it is first put online after downhole cleaning operations are completed. The failure mode was clearly an electrical short and resulting severe "burn" in the pothead/motor lead wire area. The resulting arc was of sufficient intensity to explode the pothead housing, leaving the upper motor assembly open to brine intrusion. Because this is the area where the loose motor lead connections were repaired during installation, it appears highly likely that they were partially or totally responsible for the electrical short that developed. REDA has redesigned the motor lead/pothead connectors to eliminate this potential failure in the future.

Despite the generally excellent condition of the pumping system, REDA has elected to supply all new components for the next MAGMA production well test. An entirely new 300-horsepower pumping system has been provided. This system has been completed, shipped to the REDA plant in Long Beach, and is ready for installation in the next available MAGMA production well. REDA also supplied a pump with three additional stages to increase the well output. Data from the last production test indicated that the 300-horsepower motors were operating in a slightly underloaded condition.

B. Improved REDALEAD Cable

REDA has developed an improved version of their REDALEAD power cable. The improved version has a thicker extruded lead sheath for better resistance to brine intrusion. New insulation materials have also been developed that eliminate the need for KAPTON, which degrades rapidly in the presence of hot brine. The new insulation materials are more tolerant to brine intrusion and should provide improved service life in geothermal wells. REDA has ordered a production length of this new cable; and if it is fabricated prior to the installation of the 300-horsepower system in the MAGMA well, it will be used in place of the conventional REDALEAD cable.

VII. GEOTHERMAL PUMP TEST FACILITY (GPTF)

The GPTF has been moved to the REDA pump plant in Bartlesville, Oklahoma, and has been prepared for operation. Required maintenance and preventative maintenance tasks have been performed by Barber-Nichols personnel in preparation for an extended high-temperature testing period at REDA.

REDA has fabricated two new experimental 80-horsepower motor units. These units have a totally new stator insulation package that incorporates material and design changes to improve the high-temperature mechanical and electrical integrity of the motors. Although the materials used in these new motors are proprietary, REDA has expressed a desire to run the GPTF at temperatures up to 220°C for their evaluation tests. Operation at these temperature levels would indicate REDA's confidence in the superiority of this new insulation package over the existing geothermal motor design.

Initial testing of the improved 80-horsepower motors will be performed in the GPTF with a conventional REDA cable and pothead assembly. After arrival of the first metal-sheathed power cable samples and pending successful laboratory evaluation of these samples, the conventional REDA cable will be replaced with the metal-sheathed design for the GPTF tests. This will also require the replacement of the conventional pothead with the new REDA pothead designed to accept a metal-sheathed power cable. Barber-Nichols will also supply a pressure-regulator-controlled motor lubrication system for testing on the improved 80-horsepower motor. REDA is also considering a test of their POSI-LIFE motor lubrication system during the GPTF testing period.

With the 80-horsepower unit installed in the GPTF with a metal-sheathed power cable and a pressure-regulator-controlled pressurized lubrication system, brine intrusion into the power cable should be eliminated and motor oil contraction and expansion should be adequately compensated for. To determine if significant changes in motor/cable megger readings are still occurring, the pumping system will be shut down periodically and frequent megger readings will be taken. If the megger readings remain more stabilized during these deep thermal cycles, the conjecture that brine intrusion into the cable is the proximate cause will be supported.

In summary, the upcoming tests in the GPTF at REDA will evaluate the following new components:

- Improved motor stator insulation package at test temperatures up to 220°C.
- Metal-sheathed power cable design.
- Improved pothead design for metal-sheathed power cables.
- Pressure-regulator-controlled motor lubrication system and/or REDA POSI-LIFE lubrication system.

These new components represent a dramatic step forward in the design of reliable high-temperature downhole electric submersible geothermal pumping systems.